

AUTOMATED WELD CHARACTERIZATION USING THE THERMOELECTRIC METHOD

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INTRODUCTION

The effective assessment of the integrity of welds is a complicated NDE problem that continues to be a challenge. To be able to completely characterize a weld, detailed knowledge of its tensile strength, ductility, hardness, microstructure, macrostructure, and chemical composition is needed. NDE techniques which can provide information on any of these features are extremely important. In this paper, we examine a seldom used approach based on the thermoelectric (TE) effect for characterizing welds and their associated heat affected zone (HAZ).

The thermoelectric method monitors the thermoelectric power which is sensitive to small changes in the kinetics of the conduction electrons near the Fermi surface that can be caused by changes in the local microstructure. The technique has been applied to metal sorting, quality testing, flaw detection, thickness gauging of layers, and microscopic structural analysis[1-6]. To demonstrate the effectiveness of the technique for characterizing welds, a series of tungsten-inert-gas welded Inconel-718 samples were scanned with a computer controlled TE probe. The samples were then analyzed using a scanning electron microscope and Rockwell hardness tests to characterize the weld and the associated HAZ. We then correlated the results with the TE measurements to provide quantitative information on the size of the HAZ and the degree of hardness of the material in the weld region. This provides potentially valuable information on the strength and fatigue life of the weld.

We begin the paper by providing a brief review of the TE technique and then highlight some of the factors that can effect the measurements. Next, we provide an overview of the experimental procedure and discuss the results. Finally, we summarize our findings and consider areas for future research.

INTRODUCTION TO THERMOELECTRICITY

The thermoelectric technique is based on an effect first discovered by Seebeck in 1822. Seebeck found that when two dissimilar conductors A and B make a circuit a current will flow when the junctions of the two conductors are at different temperatures (Fig. 1). The Seebeck effect occurs because at the hot end, electrons are excited to higher energies so that the Fermi-Dirac distribution has more electrons above the Fermi energy level, E_F , and fewer below. The higher energy electrons at the hot end are able to lower their energies by diffusing to the cold end. Thus, the cold end becomes negatively charged, the hot end posi-

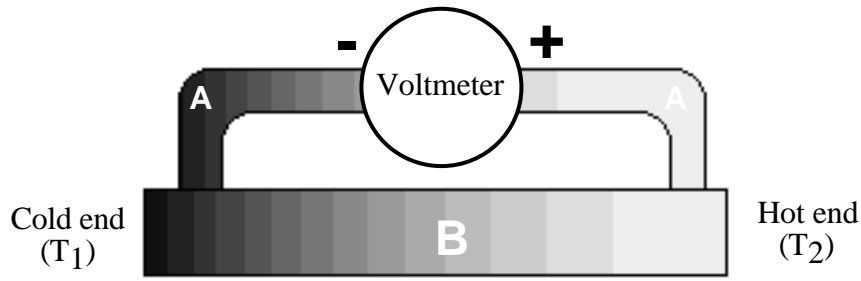


Fig. 1. Schematic of the thermoelectric circuit

tively charged and, as a result, a voltage is induced along the rod. The induced voltage creates a current equal to the voltage divided by the electrical resistance of the rod.

If the voltmeter's connecting wires, A, are of the same material as the rod, B, the temperature difference will induce the same voltage in the connecting wires as the rod and there will be no voltage across the meter. If the connectors are of a different material, a different voltage will be induced in A, and a net voltage, $E_A - E_B$, will be observed at the meter. The net voltage E_{AB} , will change with temperature and the rate of change of this voltage with temperature is defined as the thermoelectric power, S_{AB} . More precisely, the thermoelectric power is the change in emf per degree kelvin, which is also a direct measure of the change in entropy of a thermoelectric junction.

Using thermodynamic arguments the Seebeck effect, S_{AB} , can be expressed as the algebraic sum of the thermal Peltier and Thomson effects [7]. The Peltier effect is defined as the reversible change in heat content when one unit of charge crosses a junction of two dissimilar conductors. Heat is absorbed at the hotter junction and liberated at the colder one if the current flows in the same direction as the current caused by the Seebeck effect. The Thomson effect is defined as the change in heat content of a single conductor of unit cross-section when a coulomb of charge flows across it through a temperature gradient of 1°K . Further analysis allows S_{AB} to be rewritten as an integral involving only the Thomson coefficients, i.e

$$S_{AB} = \frac{dE_{AB}}{dT} = \frac{dP_{AB}}{dT} + (\sigma_A - \sigma_B) = \int_0^T \frac{(\sigma_A - \sigma_B)}{T} dT$$

where, E_{AB} is the emf generated in the circuit, T is the temperature, P_{AB} is the Peltier effect and σ_A , and σ_B are the Thomson coefficients associated with materials A and B respectively.

This Seebeck effect is a well-known physical phenomenon that is commonly used in thermocouples to make very precise temperature measurements. The idea is to use two conductors with known thermal characteristics to make a thermocouple so that the temperature difference between the conductors can be determined from a set of previously calibrated voltage values. The same phenomenon has also been applied as a tool for investigating the microstructure of metals. Akimov and Pevzner[8] developed the first thermoelectric probe over 50 years ago, thus allowing the Seebeck effect to be used as an NDE tool. To apply the thermoelectric technique for materials evaluation, a known temperature difference along with a conductor with well-defined properties is used to study characteristics of a second conductor (the test sample). Differences in the sample can show up as changes in the TE power (TEP). Three distinct phenomena can affect the TEP: the diffusion of electrons through the test sample, the temperature dependence of the contact potential, and the phonon drag effect[9]. The electron diffusion component is a volumetric effect and depends upon the dissimilar energy and velocity of electrons in a conductor which tend to restrict their flow. This effect dominates when the interaction between electrons and phonons (thermal lattice vibrations) is small. If the two junctions of the thermocouple are at the same temperature then the potential differences cancel each other. If the temperatures are not the

same, a potential difference will develop. The temperature dependence of the contact potential is a localized effect and in some cases can become even more significant than the diffusion component.

Thermal lattice vibrations (phonons) can also contribute to the TEP. If a temperature gradient exists across a conductor then more phonons will move from the hot to the cold probe against the flow of electrons causing what is referred to as phonon drag. Phonon drag is significant when the thermal lattice vibrations are not in equilibrium which typically occurs at temperatures below $\theta_D/20$ (where θ_D is the Debye temperature). Our tests were performed at temperatures significantly above the Debye temperature so that this should have little effect on our results

The practical features and conditions which effected our test results fell into two categories; those associated with volumetric effects and those associated with contact effects. The diffusion of electrons throughout the volume of the material is affected by the chemical composition, the type of heat treatment, and the hardness of the material. Contact effects such as the amount of pressure applied to the probe, probe wobble, temperature of hot and cold junctions, and probe material also impact on the results. Surprisingly, the roughness of the surface has little or no effect provided good electrical contact is made with the sample. Other effects such as stray magnetic fields and secondary thermocouples in the test instrument can also alter the low voltage measurements, but have been minimized by test equipment and will not be considered here.

EXPERIMENTAL PROCEDURE AND SET-UP

A fully automated system was developed to scan a region around the weld. The schematic of the system is given in Fig. 2 below. The system consists of a controller and a three-axis scanner that positions the TE probe on the sample. A computer program was written to automatically scan the TE probe over the sample. The program monitors three voltmeters which are attached to the TE test unit. The voltmeters keep track of the TEP, the temperature difference between the hot and cold probes, and the latch voltage, a voltage which identifies when a specified temperature difference has been reached. After the TEP for a point on the sample has been obtained the probe is then repositioned and a new value is measured. Before a new reading is taken, however, we must wait until the temperature difference between the hot and cold probe has reached a predefined upper value. The computer controlled positioning of the probe eliminated the effects of variability in probe pressure and probe wobble from the TE measurements.

The samples tested consisted of three $23.5 \times 21 \times 0.15 \text{ cm}^3$ thick Inconel 718 plates with a center weld (Fig. 3). The samples were heat treated according to ASM standard 5567B before being tungsten inert gas (TIG) welded using Inconel 718 as filler material. One sample was welded according to proper specifications producing a “good” weld. The second sample was welded with a low weld current producing a weld with poor penetration. The final plate was welded with a high weld current yielding a weld with too much penetra-

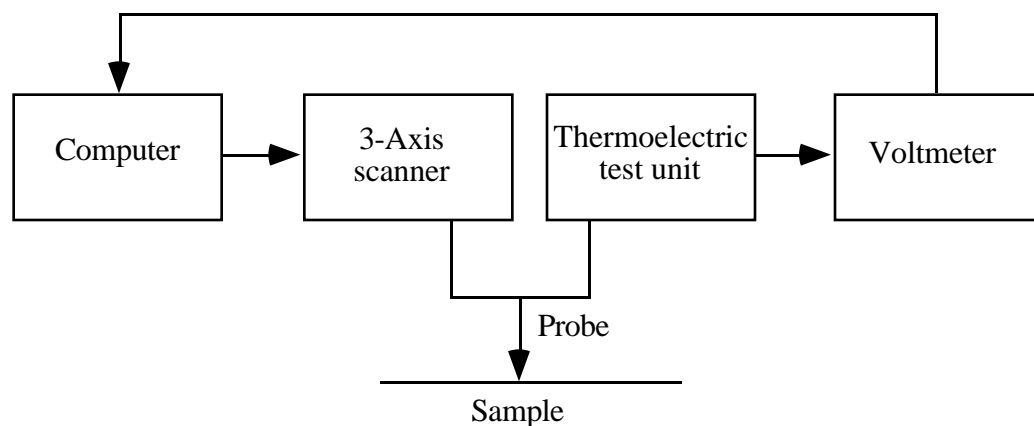


Fig. 2. Schematic of experimental set-up

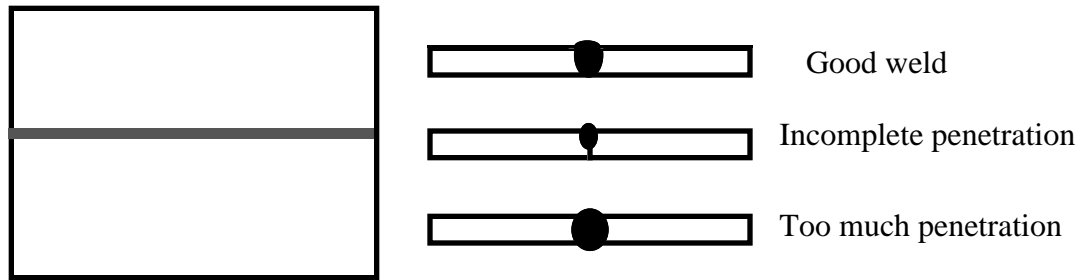


Fig. 3. Schematic of welded plate samples

tion. The samples were then cleaned so that any oxidation deposited during the welding process was removed.

In addition, two Inconel 718 samples which were not heat treated prior to TIG welding were tested. One of the samples was cut into a rectangle measuring $1 \times 2 \text{ mm}^2$ to fit into the scanning electron microscope so that a comparison between the chemical composition and the TEP could be performed.

RESULTS

All of the results were obtained with a starting temperature difference of 57°C and a final “latch” temperature of 50°C . The TE probe used to make the measurements was made of copper. Measurements of the TEP in a region $2.5 \times 16.5 \text{ cm}^2$ centered about the weld were obtained for the “good” weld and are shown in Fig. 4.

During the scan we noticed that at a few isolated points the probe did not make good electrical contact and, consequently, a value of zero was recorded for the thermoelectric power. This is highlighted in Fig. 4 by the point near the lower portion of the figure where an extremely high peak is located. To eliminate this problem and also to test the reproducibility of the measurements a smaller region was scanned and instead of one measurement, five measurements were made at each point. The high and low values were eliminated and the remaining three data points were averaged and are displayed for the “good” weld in the upper portion of Fig. 4. This eliminated the problem with poor electrical contact and also eliminated some of the noise present in the data. We should point out that even after we averaged several measurements the results did not become appreciably smoother. The variations in the TEP over the sample, however, were repeatable. Thus, we suspect that we are sensing real changes in the sample and not simply noise associated with the measurement technique.

There is a clear distinction between the base metal and the weld region which is evident by the raised portion of the data in Fig. 4. The raised region corresponds to the weld and surrounding HAZ which is roughly delineated by the sharp peaks on the boundary. The averaged results for the welds with the low and high current levels are presented in Fig. 5. In comparing the three different types of welds some qualitative differences are apparent. The size of the affected region increases with an increase in weld current and the peaks associated with the HAZ of the low penetration weld are not as pronounced as in the other two welds.

To obtain a more quantitative assessment of the results and to help facilitate comparisons with other parameters, it was necessary to examine a 2-D “slice” of the data taken on a line transverse to the weld. This was done for the three different welds and the results were then compared to Rockwell hardness measurements taken along the same cross-section. The results of this comparison are given in Fig. 6 below. The correlation between the hardness measurements and the thermoelectric power is extremely good. These results clearly identify excessively soft regions in the HAZ as is illustrated in Fig. 6 (c). We should point out that what is being shown is actually the absolute value of the TEP, since this provides a better graphical comparison to the hardness measurements.

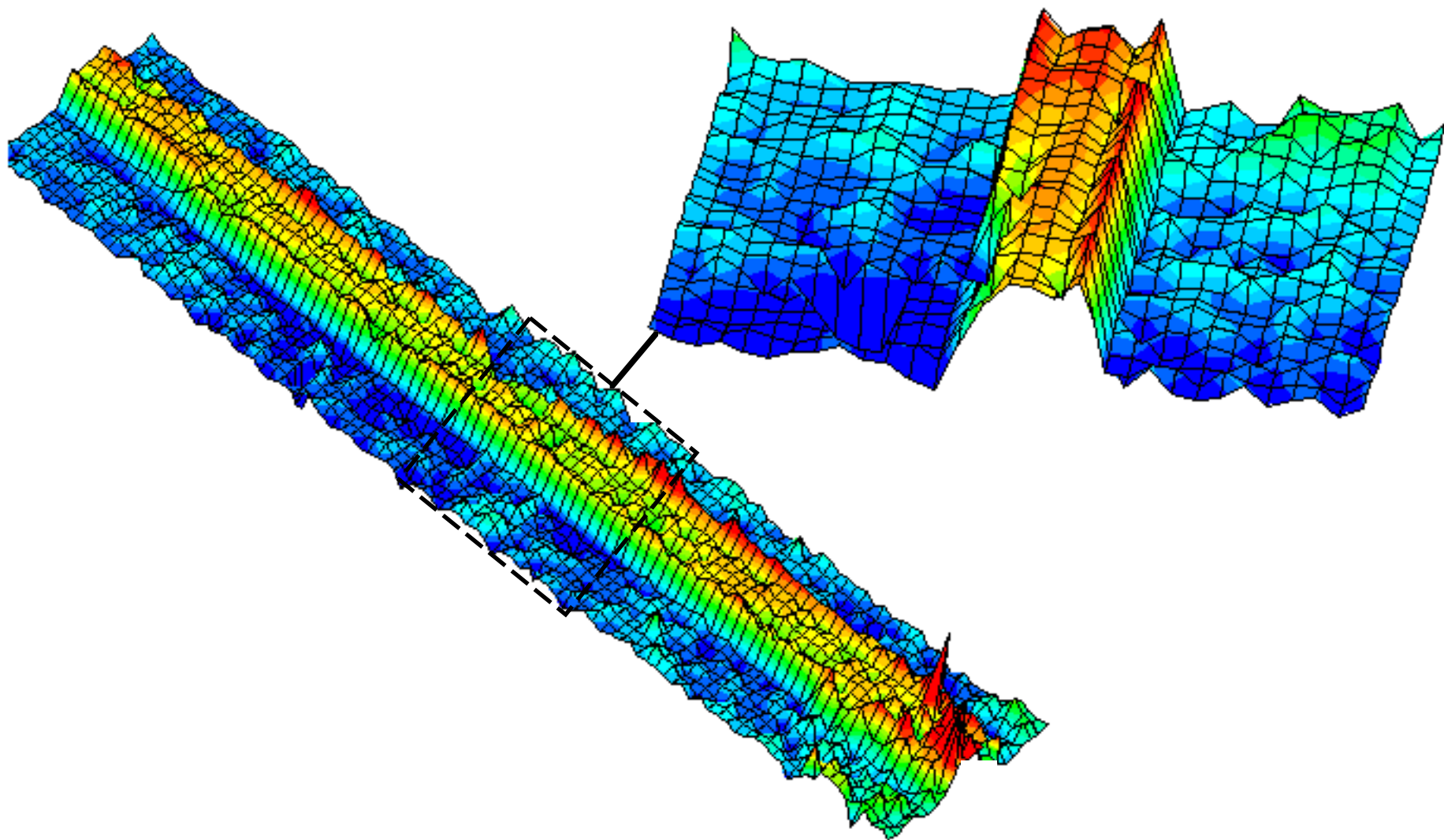


Fig. 4. Thermoelectric power scan across a region around a “good” weld

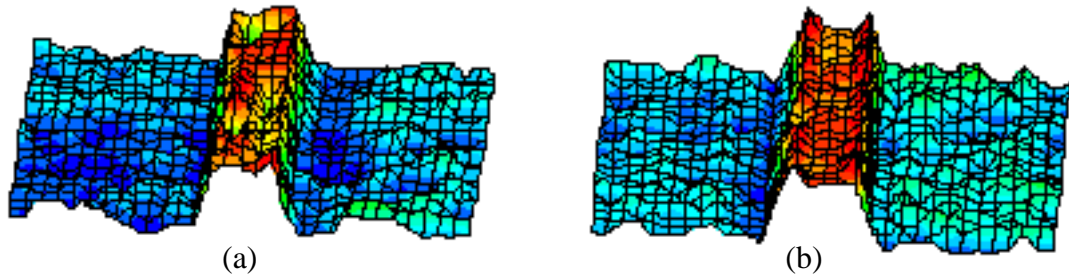
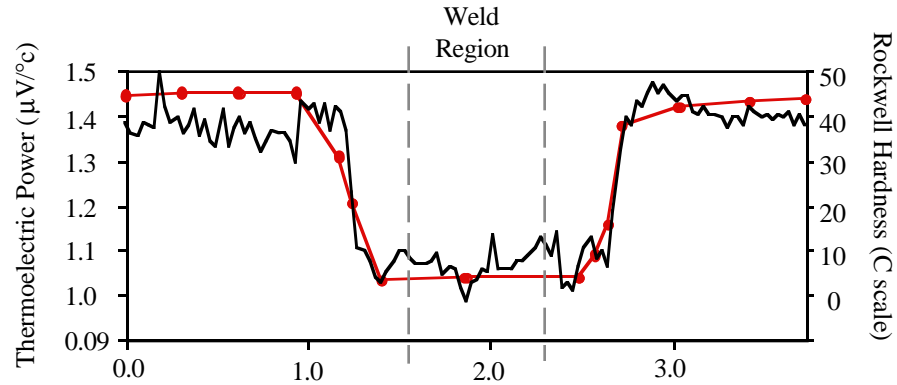
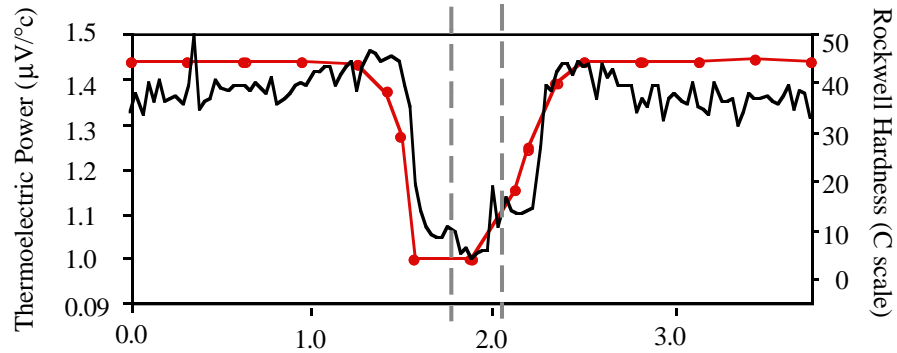


Fig. 5. Thermoelectric power scans for (a) low weld current and (b) high weld current

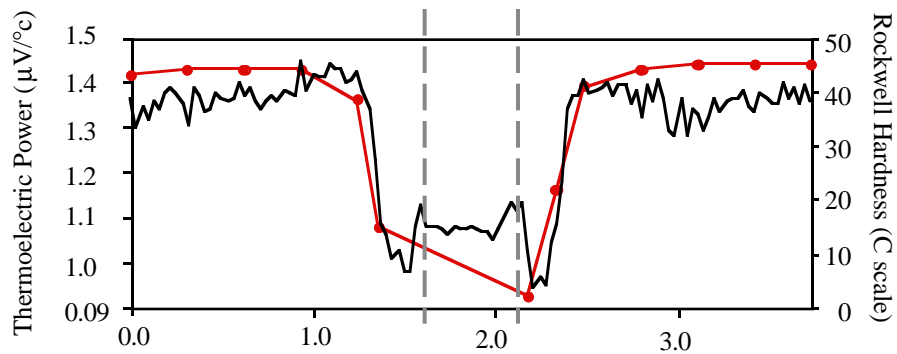
From these results it is possible to make quantitative, as well as qualitative comparisons between the three welds. It is also possible to correlate a particular TEP value with a specific hardness value and, consequently, identify possible problem areas in the weld. Another feature that is evident from the graphs is the large local variations of the TE measurements as the weld is traversed. At first, we attributed this to noise, but subsequent mea-



(a) Good weld



(b) Low weld current



(c) High weld current

Position across weld (cm)

— Thermoelectric Power —●— Mechanical Hardness Measurement

Fig. 6. Comparison of thermoelectric power and Rockwell hardness measurements

surements along the same path revealed that the local changes were repeatable. Thus, we are convinced that these changes are related to variations in properties of the Inconel 718.

The effect of changes in the chemical composition across the weld on the TE measurements has also been investigated. We analyzed the sample that was not heat treated by putting it in a scanning electron microscope and using Energy Dispersive Analysis by X-ray (EDAX) to determine the chemical composition at points along the weld. The following elements were found to be present in different amounts across the weld: Al, Si, Nb, Mo, Ti, Cr, Fe, Ni, and at two isolated points Cu. The relative percentage of each relevant element was then compared to the TE measurements and the results are given in Fig. 7 below. Only a slight correlation was found for some of the elements. Niobium, molybdenum, and to a slight extent titanium showed some correlation with the TE measurements, while the remaining elements did not correlate well with the data. The overall results were not conclusive and further tests need to be performed.

SUMMARY

A strong correlation between the TEP and the hardness of Inconel 718 was established. The technique proved to be very effective as an automated NDE tool for characterizing the HAZ. It provides high resolution indications of the “soft” regions around the weld where failure can occur and produces fairly repeatable results. Only a slight correlation between the TEP and the chemical composition of the metal could be seen. Thus, for Inconel 718 we conclude that hardness is the dominant parameter measured by the TE technique and that slight variations in chemical composition only have a small impact on the

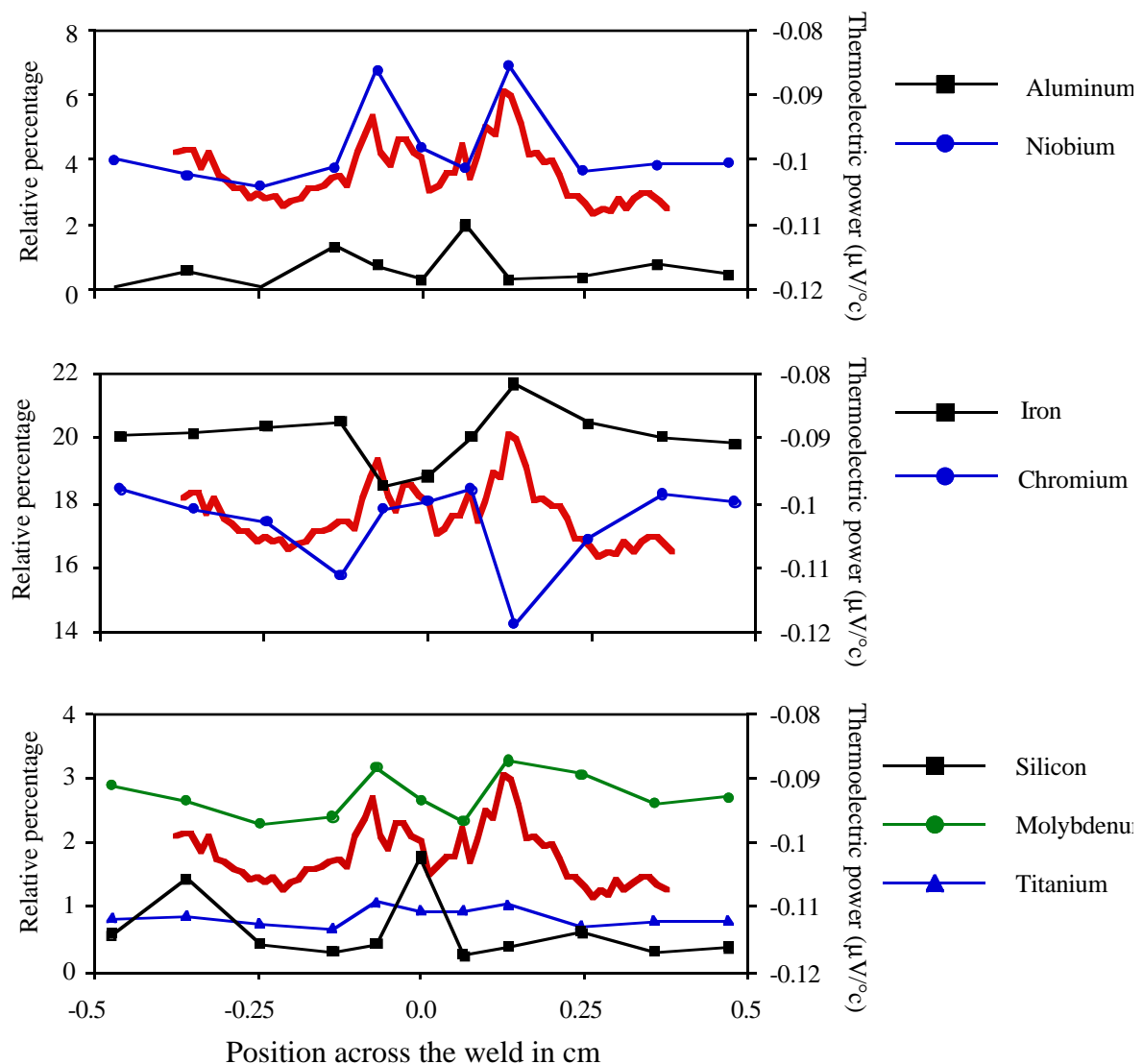


Fig. 7. Comparison of thermoelectric power and chemical composition

measurements.

An area for future study will include establishing calibration standards to quantify the degree of hardness in terms of the TEP. Changing the probe tip to a similar material may increase the sensitivity of the TE measurements to changes in Inconel 718. In particular, this may increase the sensitivity of the technique to slight changes in the chemical composition across the weld which would be very helpful in characterizing the integrity of the weld. Finally, fatigue tests on the samples should be performed to determine what predictions can be made from the TE results regarding weld failure.

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